Cold Gas Reaction Control System for the Near Earth Asteroid Scout CubeSat

Brandon C. Stiltner[1] and Ben Diedrich.[2]
Jacobs ESSSA Group / NASA MSFC, Huntsville, AL, 35812

Juan Orphee[3], Andrew Heaton[4], Chris Becker[5], and Ivan Bertaska[6]
NASA MSFC, Huntsville, AL, 35812

This paper describes the Attitude Control System (ACS) for the Near Earth Asteroid (NEA) Scout cubesat with particular focus on the Reaction Control System (RCS). NEA Scout is a 6U cubesat with an 86 square-meter solar sail. NEA Scout will launch on Space Launch System (SLS) Exploration Mission 1 (EM-1), currently scheduled to launch in 2018. The spacecraft will rendezvous with an asteroid after a two year journey, and will conduct science imagery. The ACS consists of three major actuating subsystems: a Reaction Wheel (RW) control system, a Reaction Control System (RCS), and an Active Mass Translator (AMT) system. The three subsystems allow for a wide range of spacecraft attitude control capabilities, needed for the different phases of the NEA-Scout mission. The RCS performs a number of critical functions during NEA Scout's mission. These requirements are described and the performance for achieving these requirements is shown. Moreover, NEA Scout employs a solar sail for long-duration propulsion. Solar sails are large, flexible structures that typically have low bending-mode frequencies. This paper demonstrates a robust performance while avoiding excitation of the sail's structural modes.

Nomenclature

A	=	amplitude of oscillation
a	=	cylinder diameter
C_p	=	pressure coefficient
Cx	=	force coefficient in the *x* direction
Cy	=	force coefficient in the *y* direction
c	=	chord
dt	=	time step
Fx	=	*X* component of the resultant pressure force acting on the vehicle
Fy	=	*Y* component of the resultant pressure force acting on the vehicle
f, g	=	generic functions
h	=	height
i	=	time index during navigation
j	=	waypoint index
K	=	trailing-edge (TE) nondimensional angular deflection rate

I. Introduction

The Near Earth Asteroid (NEA) Scout spacecraft is a 6U cubesat that is currently under development by NASA as a joint effort between NASA Marshall Space Flight Center (MSFC) and the Jet Propulsion Laboratory (JPL).

[1] GN&C Engineer, Jacobs ESSSA Group / NASA MSFC, AIAA Senior Member.
[2] GN&C Engineer, Jacobs ESSSA Group / NASA MSFC.
[3] Insert Job Title, Department Name, Address/Mail Stop, and AIAA Member Grade for third author.
[4] Insert Job Title, Department Name, Address/Mail Stop, and AIAA Member Grade for fourth author (etc.).
[5] Insert Job Title, Department Name, Address/Mail Stop, and AIAA Member Grade for fourth author (etc.).
[6] Insert Job Title, Department Name, Address/Mail Stop, and AIAA Member Grade for fourth author (etc.).

NEA Scout will launch on Space Launch System (SLS) Exploration Mission (EM) 1, currently scheduled to launch in 2018. NEA Scout's primary mission objective is to rendezvous with a near Earth asteroid and perform science imagery. Specifically, its scientific objectives are to better characterize the target asteroid's orbit, and to take pictures of the asteroid's surface. This paper discusses the overall Attitude Control System (ACS) for NEA Scout. Specific attention is given to the Reaction Control System (RCS), which uses a cold-gas propellant for attitude control.

The remainder of this paper is organized as follows. Section II provides an overview of the NEA Scout cubesat and its mission. Section III provides an overview of ACS hardware, which disucsses the primary control actuators and control sensors. This section provides an in depth overview of the RCS hardware. Section IV details the RCS responsibilities and control system design. Section V details the RCS performance against the requirements listed in Section IV. In Section VI, a brief summary of solar sail flex-dynamics is provided, along with how the control design to avoid exciting these dynamics. Last, remaining conclusions are provided in Section VII.

II. NEA Scout Overview

NEA Scout is a 6U cubesat that will use a solar-sail for propulsion. An image of the NEA Scout cubesat is shown in Figure 1 below. In the image, most of the ACS hardware is called out. As shown, there are 3 primary control actuators on NEA Scout: the Reaction Wheel (RW) control system, the RCS, and the Active Mass Translator (AMT). The functions of each control actuator are discussed in Section III. Also shown are the attitude determination sensors: three coarse sun sensors, an Inertial Measurement Unit (IMU), and a star tracker. These devices are also described in Section III.

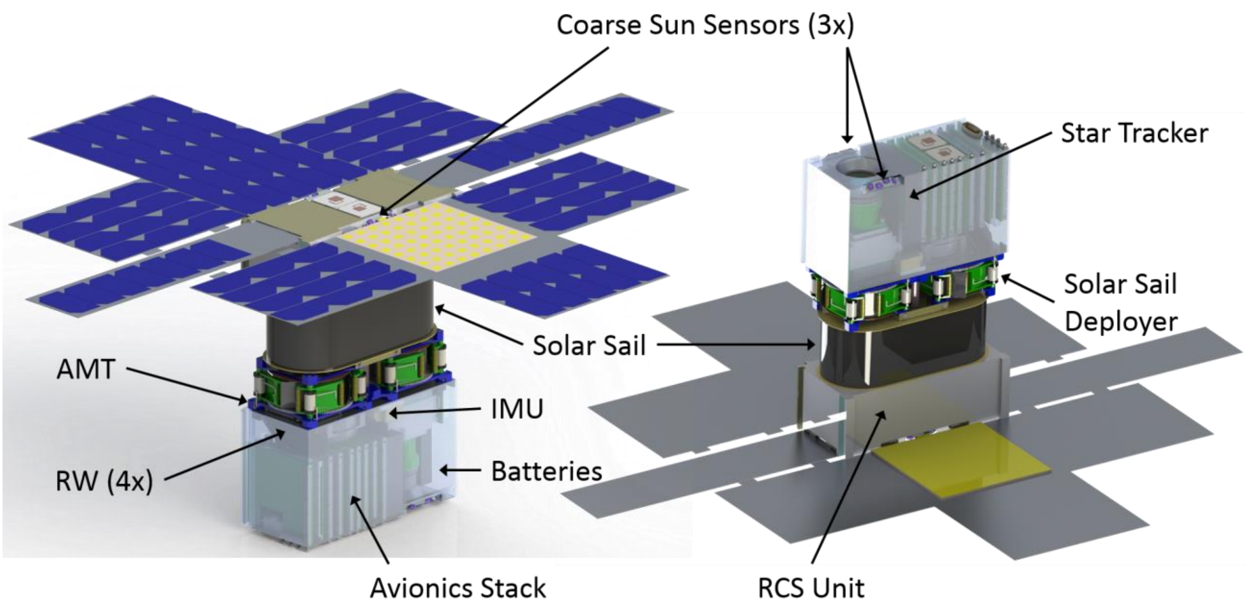

Figure 1: CAD images of NEA Scout showing the spacecraft in two different orientations and calling out the names and locations of various spacecraft components.

NEA Scout is divided into three major pieces as shown in Figure 2. Starting at the bottom of the figure, the solar panels are attached to the RCS unit. The RCS unit occupies approximately 2U of the spacecraft's volume and is outlined in green. Just above the RCS unit is the solar sail and sail deployer. These items occupy the middle 2U of the spacecraft's volume and are outlined in blue. Last, the top portion outlined in orange is the spacecraft's avionics bus, and occupies the remaining 2U of volume. This portion contains the science camera, the star tracker, flight computer, reaction wheel assembly, and other . For the majority of NEA Scout's mission, this side of the spacecraft will be pointed away from the sun. Put another way, this side of the spacecraft will be in the shadow of the solar sail. Figure 3 provides an image of NEA Scout before and after the solar sail is deployed.

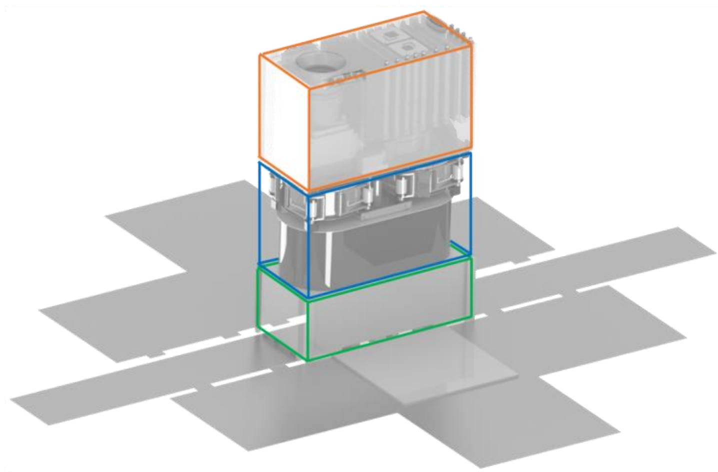

Figure 2: CAD image of NEA Scout showing calling out the three major pieces of the spacecraft: RCS unit (green), solar sail and deployer mechanism (blue), and avionics bus (orange).

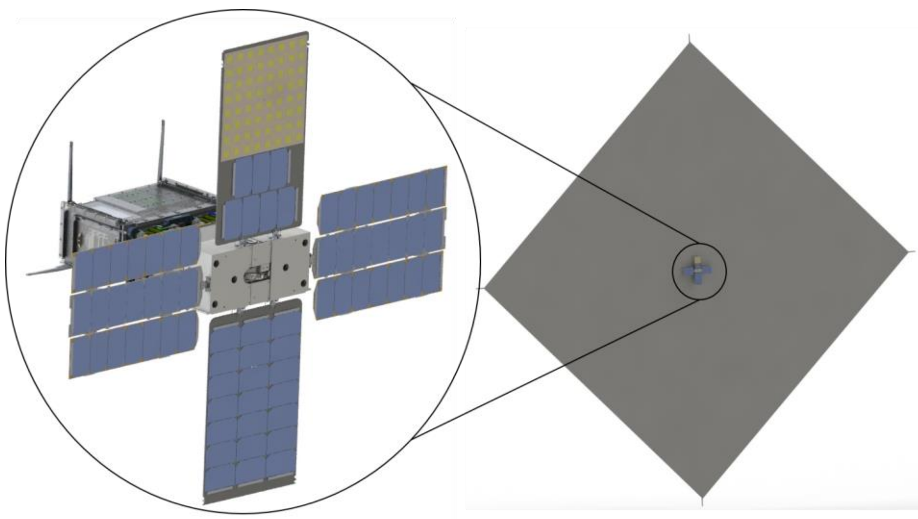

Figure 3: Image of the NEA Scout cubesat before solar sail deployment (left), and after solar sail deployment (right).

A. NEA Scout Mission Overview

Information will be added here for final paper.

III. NEA Scout ACS Overview

A. Attitude Control Effectors

1. Reaction Wheel System

Information will be added here for final paper submittal.

2. RCS

The RCS unit is shown in Figure 1 and Figure 2. The unit occupies approximately 2U of volume on NEA Scout and contains 1.25kg of propellant when full. The propellant is refrigerant R236fa . A conceptual image of the RCS unit is shown in Figure 4. The four circular features at the corners represent the attitude control jets, and arrows are used to depict the direction of thrust for each jet. The attitude control jets are arranged so that firing any pair generates torque about one of the spacecraft body axes. For example, firing jets 1 and 2 create a positive Y-axis torque, and jets 2 and 4 create a positive Z-axis torque. The two circular features in the center of the RCS unit are the axial jets, with force components along the negative z-axis (into the page).

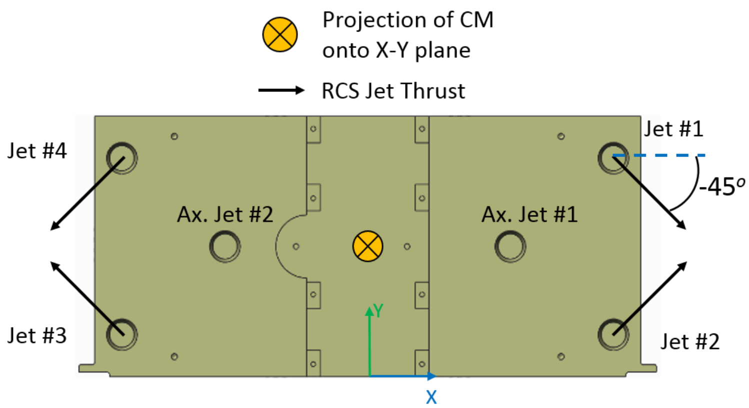

Figure 4: Conceptual image of the RCS unit showing the four attitude control jets and two axial jets. The force directions are visualized as black arrows, and the projection of the spacecraft Center of Mass (CM) is also shown on the RCS unit.

3. AMT

Information will be added here for final paper submittal.

B. Attitude Determination Sensors

1. Sun Sensors

Information will be added here for final paper submittal.

2. IMU

Information will be added here for final paper submittal.

3. Star Tracker

Information will be added here for final paper submittal.

IV. RCS Control System Responsibilities and Design

A. RCS Responsibilities

NEA Scout uses a cold gas RCS to control the spacecraft's attitude at various times during the mission. Specifically, the RCS has five responsibilities:

- Initial spacecraft detumble
- Initial sun-pointing and attitude hold
- Trajectory Correction Maneuver (TCM)
- Reaction wheel momentum desaturation
- Safe mode operation

NEA Scout will be ejected from SLS with some residual angular rates (up to 10 degrees per second on each body axis). The spacecraft power state will also be unknown, as the vehicle could be in storage for up to one year prior to SLS launch. Therefore, the first and second operations are to null the spacecraft angular rates and point toward the sun to charge the batteries. After achieving a net-positive charge state, the reaction wheels will take over as the primary actuator for the spacecraft.

While the reaction wheels are the primary actuator, attitude control is handed over to the RCS at certain phases of the mission. One example is during the TCM. This maneuver is performed to achieve the desired Earth-Moon orbit, and occurs shortly after ejection from SLS. Here, the axial jets will fire continuously to provide the necessary ΔV, while the RCS jets maintain the spacecraft's attitude during the maneuver. Attitude control is performed by the RCS jets during the TCM because the torques are too high for the reaction wheels.

For the majority of the mission, the reaction wheels are the primary attitude control effectors. However, throughout the mission, the RCS is used to desaturate the reaction wheels as needed. Furthermore, the RCS is also used for any safe mode operations. Safe mode operations are those that occur due to unexpected events, such as a flight computer reboot or other unforeseen problem that occurs during flight. As of the time of writing this paper, the NEA Scout safe mode is currently being defined, but will likely be a maneuver to point-and-hold the solar panels toward the sun.

B. RCS Control Design

NEA Scout uses simple logic known as a phase-plane control system for the RCS. This type of control is sometimes referred to as a Schmitt Trigger or a bang-off-bang controller. A phase-plane controller is best described visually as shown in Figure 5. The figure depicts a Cartesian coordinate frame with the attitude error on the x-axis and angular rate error on the y-axis. The red lines on the plot denote the switching lines, while the grey inner-region denotes the quiescent region, or deadband. On NEA Scout, each body axis has a separate phase-plane, and the angular rate error and attitude error are evaluated for each vehicle body axis. If the values are outside the deadband, a pair of RCS jets are opened, driving the system back toward the quiescent region.

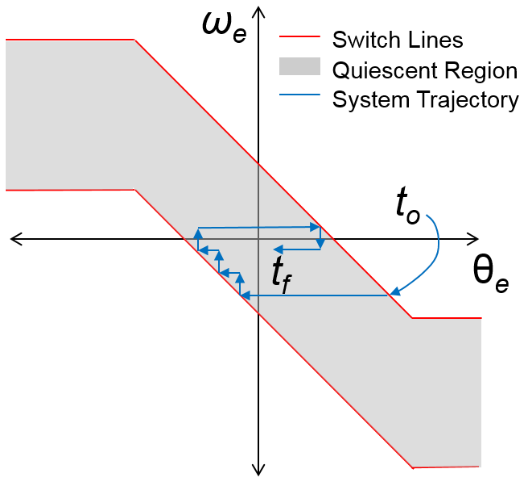

Figure 5: A theoretical Phase Plane diagram to illustrate the concept of the switching lines and quiescent region. The blue arrows depict a notional system trajectory as subject to a phase plane control system.

A theoretical system trajectory is shown in Figure 5 depicted with blue arrows. At t_0, the rate and attitude errors are outside the deadband, so a pair of RCS jets are opened. This drives the state into the 4th quadrant of the phase-plane until reaching the upper switching line. At this point, the jets are closed and the system is quiescent. But because the angular rate error is non-zero, the system's attitude error drifts across the deadband until reaching the lower switching line. The system follows a *stair case* along the lower switching line caused by opening and closing the jets. This effect is the result of a digital (non-continuous) control system. Once the angular rate error is positive, the attitude drifts back across the phase plane toward the upper switching line. If there are no disturbance torques on the vehicle, this system will continue to encircle the origin of the phase-plane as is partially shown in the figure.

V. RCS Control Performance

A. Initial Detumble and Sun Pointing

Information will be added here for final paper submittal.

B. TCM

Information will be added here for final paper submittal.

C. Safe mode Operations

Information will be added here for final paper submittal.

D. Sail Flex Dynamics

Information will be added here for final paper submittal.

VI. Conclusions

Information will be added here for final paper submittal.

Acknowledgments

Information will be added here for final paper submittal.

References

[1] Bryson, A. E., *Control of Spacecraft and Aircraft*, Princeton University Press, New Jersey, 1994, pp. 34-36.